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(54) VARIABLE ELECTRICAL DELAY LINE

(71) We, WESTINGHOUSE ELECTRIC CORPORATION of Westinghouse Building, Gateway Center, Pittsburgh, Pennsylvania, United States of America, a company organised and existing under the laws of the Commonwealth of Pennsylvania, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to variable electrical delay lines and, more specifically, to delay lines the phase dispersion characteristic of which can be varied.

Delay lines in the form of meander lines are well known and are generally constructed by forming the center strip conductor of a planar stripline transmission line in a pattern which provides a plurality of spaced, generally parallel, electrically inter-acting segments. The meander line exhibits phase dispersive characteristics in that the total time delay introduced in a signal transmitted along the line is a nonlinear function of the signal frequency.

For example, if two in-phase signals of different frequencies such as first and second harmonic signals are transmitted through a dispersive meander line, the two output signals from the line will be out of phase. The relative phase difference between the two output signals depends upon the dispersive characteristics of the meander line at the frequencies of the applied signals and is a function of the physical configuration of the meander line. Thus, to vary the dispersive characteristics of a meander line at a predetermined frequency, the physical configuration of the line must be varied. Similarly, to retain desired dispersive characteristics of a meander line at different frequencies, the physical configuration of the meander line must be varied.

It may be desirable to vary the dispersive characteristic which a meander line presents to a fixed frequency signal or to retain a particular dispersive characteristic over a range of frequencies. For example, it may be desirable to phase shift a second harmonic signal by a predetermined amount relative to the first harmonic or fundamental signal to achieve second harmonic signal suppression. In an application such as harmonic suppression in a radar system, the fundamental signal frequency may be variable within a predetermined band and, to be effective, the phase dispersion characteristics of the meander line may necessarily have to be variable. Available dispersive meander line signal delay systems cannot provide this capability.

These and other objects and advantages are accomplished through the provision of a delay line having a selectively variable physical configuration. More specifically, a first substrate is provided with an electrically conductive strip formed with a plurality of electrically interactive segments or sections along one surface thereof. A second substrate is disposed in at least partially overlying relation with the strip of the first substrate. The second substrate is provided with electrically conducting means contacting the strip of the first substrate for varying the electrical interaction between the segments thereof in response to relative movement between the two substrates.

The interaction varying means is preferably another electrically conductive strip formed with a plurality of electrically interactive segments or sections disposed along the surface of the second substrate. The strip along the surface of the second substrate is preferably substantially a mirror image of the strip along the surface of the first substrate so that the strips are substantially coextensive and coincide in one position of the first substrate relative to the second substrate.

In utilizing the variable dispersion delay line for the suppression of second harmonic power in power amplifier chains, an output signal from a signal source such as a first power amplifier is coupled to an amplifier such as a second power amplifier through the variable dispersion delay line. The output signal from the signal source includes a fundamental frequency component and a second

harmonic frequency component, and the dispersive characteristic of the variable dispersion delay line is adjusted to obtain approximately a 180° phase displacement between the fundamental and second harmonic frequency components. The second harmonic power generated by the second power amplifier is thereby suppressed by the phase shifted second harmonic frequency component of the signal coupled from the signal source to the amplifier.

The invention accordingly resides broadly in a variable electrical delay line comprising a first member having a first electrical conductor which provides a plurality of electrically interactive, phase dispersive segments spaced along the length thereof; a second member overlying at least one of said segments of said first member and including a second electrical conductor overlying said segment of the first conductor for varying the electrical interaction between the segments of the first conductor as a result of relative movement between said first and second members.

A preferred embodiment of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:—

Figure 1 is a perspective view of a prior art dispersive meander line;

Fig. 2A is a graph illustrating the delay characteristics of dispersive and nondispersive delay lines;

Fig. 2B is a graphical representation of typical waveforms of first and second harmonic signals illustrating the effects of transmission through dispersive and nondispersive delay lines;

Fig. 3 is a functional block diagram of an arrangement for suppressing second harmonic signals;

Fig. 4 is an exploded, perspective view of a variable dispersion meander line;

Figs. 5A and 5B are views in cross-section (to a larger scale than Fig. 4) of the variable dispersion meander line of Figure 4 illustrating two selected positions thereof;

Fig. 6 is a graph illustrating the phase difference introduced between first and second harmonic signals as a function of the physical characteristics of the variable dispersion meander line of Figure 4; and

Fig. 7 is a graph illustrating the variations in characteristic impedance of the variable dispersion meander line of Figure 4 as a function of the physical characteristics thereof.

A meander line may typically be utilized in a microwave system as a delay or phase shifting element. As in Figure 1 where a typical meander line is illustrated, an electrically conductive strip 10 may be encapsulated in a substrate 12 of a low loss, microwave dielectric material. The substrate 12 may be any suitable dielectric material having a conductive outer cladding, e.g., copper-clad polytetrafluoroethylene-fiber glass. The conductive strip 10 may be provided with terminals or connectors to a microwave circuit. The strip 10 is configured in a zig-zag or "meander line" pattern to provide a plurality of spaced, substantially parallel, electrically interactive or coupled phase dispersive segments 16 between the ends 14 thereof. Each segment 16 has length designated L, determined in a conventional manner by the frequency for which the meander line is designed, and a strip width W which, in conjunction with a gap spacing S and an intersegment pitch dimension D, primarily determines the dispersive characteristics of the meander line.

A meander line such as that illustrated in Figure 1 exhibits a phase dispersive characteristic in that the delay or phase shift introduced between the ends 14 of the meander line is nonlinear as a function of the frequency of the signal coupled therethrough. This phase dispersive characteristic of a meander line is a function of the physical configuration of the meander line as well as the frequency of the applied signal. For example, as the ratio of the width W of the strip 10 to the pitch D of the interactive segments 16 is increased from zero to one, the phase characteristics vary from nondispersive to resonant. Similarly, the phase dispersion of the meander line is inversely related to the ratio of gap width S to pitch D, i.e., as the ratio S/D decreases, the phase dispersion of the meander line increases.

The dispersive characteristic of a meander line as compared to a nondispersive delay line is illustrated in Figure 2A. Referring now to Figure 2A, a linear relationship exists between the frequency of an applied signal expressed in terms of angular frequency ω and the electrical length of a nondispersive delay line expressed in terms of relative phase ϕ as is indicated by the line 18. Thus, it can be seen that for a nondispersive delay line, a signal having an angular frequency ω_1 and a signal having an angular frequency $2\omega_1$ will be phase shifted by the same relative amounts because of the linear delay characteristics of a nondispersive delay line at different frequencies.

This linear relationship may be more clearly understood with reference to Figure 2B wherein a first signal 20 at a fundamental frequency and a signal 22 at the second harmonic thereof are graphically illustrated. With these two signals applied to a nondispersive delay line, each signal is linearly delayed or phase shifted and the phase of the fundamental signal 20 relative to the phase of the second harmonic signal 22 will be the same both before and after the signals are delayed.

A dispersive delay line, on the other hand,

exhibits a non-linear delay for signals of different frequencies and results in the curve 24 of Figure 2A. Thus, with the same fundamental frequency signal 20 and the same second harmonic signal 22 applied to a dispersive delay line having the characteristic curve 24 illustrated in Figure 2A, a relative phase shift $\Delta\phi$ will be introduced between the fundamental and second harmonic output signals. This relative phase displacement may be more clearly seen with reference to Figure 2B.

Referring to Figure 2B, the fundamental signal 20 and the second harmonic signal 22 may be applied to the phase dispersive meander line of Figure 1. Assuming that each segment 16 of the meander line of Figure 1 exhibits the phase dispersive characteristics illustrated by the curve 24 in Figure 2A, the output signals from the meander line will have a relative phase displacement $N\Delta\phi$ (where N is the number of segments 16) as is indicated by the phase relationship between the fundamental signal 20 and the nonlinearly delayed second harmonic signal 26 illustrated in phantom in Figure 2B.

It has been found that the nonlinear dispersion characteristic of a meander line is useful in microwave amplifying circuits for the suppression of second harmonic power generated in power amplifier chains. With reference to Figure 3, for example, a power amplifier 28 may provide a relatively high power microwave output signal having excessive second harmonic signal content. To reduce the second harmonic signal content of the output signal, the output signal from the power amplifier 28 may be applied to a second high power output amplifier 30 through a variable phase dispersion meander line 32 hereinafter described in greater detail.

In operation, the phase relationship between the first and second harmonic signals from the power amplifier 28 may be adjusted through adjustment of the phase dispersion characteristics of the variable phase dispersion meander line 32. When this phase relationship is properly adjusted so that the second harmonic signal is approximately 180° out of phase with the fundamental signal, the second harmonic power generated in the output amplifier 30 may be significantly reduced by the injected, phase shifted second harmonic signal from the variable phase dispersion meander line 32. While, in general, it is necessary to control the amplitude as well as the phase of the injected second harmonic signal to achieve complete cancellation, a significant reduction of more than 10 dB in the second harmonic content of the output amplifier 30 has been demonstrated by adjusting only the phase of the injected harmonic.

The variable phase dispersion meander line 32 of Figure 3 may be constructed in accordance with the preferred embodiment of the present invention illustrated in Figures 4 and 5. Referring now to Figure 4, the variable phase dispersion meander line 32 of the present invention may include a first substrate 34 having a thickness A and having an electrically conductive strip 36 embedded in one surface 35 thereof. As can be seen more clearly in Figures 5A and 5B, the electrically conductive strip 36 is preferably embedded in the substrate 34 sufficiently so that an outer surface of the strip 36 is flush with the surface 35 of the substrate 34.

The strip 36 is desirably configured to provide a plurality of spaced, substantially parallel, electrically interactive phase dispersive segments 36′ along the length thereof. As is illustrated in Figure 5A, the segments 36′ may each be defined as having a width W and may be separated by a gap separation distance S. The separation distance S plus the width W define a distance D (the pitch dimension) between corresponding edges of the segments 36′, e.g., between the rightmost or leftmost edges of the segments 36′.

A second substrate 38 having an electrically conductive strip 40 embedded in and flush with one surface 37 thereof may provide a means for varying the phase dispersive characteristics of the segments 36′ embedded in the first substrate 34. The electrically conductive strip 40 is preferably configured as a mirror image of the strip 36 with an identically formed plurality of electrically interactive, phase dispersive segments 40′ along the length thereof. With the surfaces 35 and 37 of the respective substrates 34 and 38 disposed in abutting relation as is illustrated in Figure 5A, the conductive strips 36 and 40 are disposed in electrical contact and thus provide an electrically continuous, substantially coextensive strip. By moving one of the substrates 34 and 38 relative to the other as is illustrated in Figure 5B, the ratio of S/D may be varied to vary the dispersion characteristics of the meander line.

While the segments 40′ are preferably formed from an electrically continuous strip 40, it can be seen that the portions of the strip 40 extending longitudinally of the substrate do not directly affect the S/D ratio when the substrates 34 and 38 are relatively moved. Thus, the segments 40′ need not be electrically connected to obtain a movement responsive variation in the S/D ratio and thus the phase dispersive characteristics of the meander line. The illustrated embodiment is, however, preferred since losses due to sharp corners are minimized with the illustrated embodiment.

The substrates 34 and 38 may be formed from a suitable low loss, microwave dielectric material such as commercially available composite of copper-clad, polytetrafluoroethylene-fiber glass. The conductive strips 36 and 40 may be formed from any suitable, highly

electrically conductive material, preferably copper with a gold plating thereover. Moreover, the corners of the transmission line formed by the conductive strips 36 and 40 may be chamfered as illustrated to reduce reflections.

With continued reference to Figure 4, the substrate 34 and 38 may be accurately slidably positioned relative to each other for the purpose of accurately varying the dispersion characteristics of the meander line by slidably mounting one of the substrates, e.g., the substrate 38, in a support frame generally indicated at 42. The support frame 42 may include a relatively flat support plate 44 having a transversely extending flange 46 at one end thereof and spacing members 48 along each edge thereof. The spacing members 48 may be substantially identical in thickness to the thickness A of the substrate 38 and may slidably receive the substrate 38 therebetween with a surface 50 of the substrate 38 resting in abutment with a surface of the support plate 44.

A laterally extending flange 52 may be provided at one end of the substrate 38, and threaded apertures generally indicated at 54 and 56 may be provided through the respective flanges 46 and 52. A threaded adjustment screw 58, for example a machine screw threaded in opposite directions at opposite ends thereof, may be threaded into the threaded apertures 54 and 56 to provide accurate movement of the substrate 38 along the channel formed by the spacers 48 in response to rotation of the adjustment screw 58. The substrate 34 may then be conventionally fastened to the support frame 42 so that the substrate 34 is fixed relative to the support frame 42. For example, threaded apertures 60 may be provided in the spacers 48 and correspondingly positioned apertures 62 may be provided through the substrate 34. The substrate 34 may thereby be bolted to the spacer 48 so that the surfaces 35 and 37 of the substrates 34 and 38 are in sliding engagement.

In operation, the substrates 34 and 38 of the variable dispersion meander line of Figure 4 may be initially positioned so that the strips 36 and 40 are substantially co-extensive in width as is illustrated in Figure 5A. To facilitate an understanding of the invention, it may be assumed that the variable dispersion meander line is to be employed to reduce the second harmonic signal content of an amplified signal as was previously described in connection with Figure 3. In this connection, an amplified microwave signal from a first power amplifier may be applied through the variable dispersion meander line of Figure 4 and the output signal therefrom may be applied to a second power amplifier. The output signal from the second power amplifier may be monitored for second harmonic signal content and the relative positions of the substrates 34 and 38 may be adjusted by turning the adjusting screw 58.

As the adjusting screw 58 is rotated, the substrates 34 and 38 and the electrically interactive segments 36′ and 40′ move relative to each other resulting in a change in the S/D ratio and the dispersive characteristics of the meander line. As is illustrated in Figure 6, the phase delay of the fundamental signal relative to its second harmonic signal for each electrically interactive segment of the variable dispersion meander line may be nonlinearly varied over a relatively large range by changing this S/D ratio.

With continued reference to Figure 6, the phase difference $\Delta\phi$ for various ratios of substrate thickness 2A to coupled segment pitch D varies in a decreasing manner with an increase in the ratio of S/D. Thus, for a ratio of 2A/D=2.9 (curve 66) the phase difference $\Delta\phi$ for each interacting segment of the variable dispersion meander line may be varied between approximately 35° and 90° by varying the ratio of S/D between 0.5 and 0.01. Similarly, curves 68 and 70 indicate the variable phase dispersion characteristics obtained in accordance with the present invention for ratios of 2A/D equal, respectively, to 1.0 and 0.5.

A 180° phase difference between the fundamental and the injected second harmonic signals provides maximum second harmonic signal cancellation. Thus, with a variable dispersion meander line having the characteristics illustrated by the curve 66 of Figure 8, three interacting segments may be provided to permit a variation of phase difference over a range of between 105° and 270°, i.e., three times the quantity 2A/D for one meander line section. The S/D ratio may then be varied within this range by adjusting the screw 58 to provide a total of 180° phase displacement between the first and second harmonic signals. In the exemplary meander line having the characteristics illustrated by the curve 66, this S/D ratio is approximately 0.15 since this ratio provides a phase difference $\Delta\phi$ of approximately 60° for each of the three interacting segments.

The practical range over which the ratio S/D may be varied is determined by the variation in characteristic impedance which can be tolerated in the particular application of the variable dispersion meander line. As the S/D ratio is varied, the characteristic impedance of the variable dispersion meander line varies and may result in an undesirable loss of power should too great an impedance mismatch result from varying the S/D ratio.

In Figure 1 the variation of the characteristic impedance Z_o of a variable dispersion meander line constructed in accordance with the teachings of the present invention is illus-

trated as a function of the ratio S/D for ratios of 2A/D equal to 2.0 (curve 72), 1.0 (curve 74) and 0.5 (curve 76). Referring now to Figure 7 wherein the product of the characteristic impedance Z_0 times the square root of the relative dielectric constant $\sqrt{\varepsilon r}$ of the substrate material is plotted as a function of the ratio S/D, it can be seen that for a ratio of 2A/D=2.0 (curve 72), the characteristic impedance-relative dielectric constant product may vary from approximately 46 ohms at an S/D ratio of 0.01 to approximately 130 ohms at an S/D ratio of 0.5. It can be seen that with the exemplary meander line previously discussed in connection with Figure 6 adjusted to an S/D ratio of 0.15, the square root of the characteristic impedance-relative dielectric constant product is approximately 80 ohms.

Assuming that a typical substrate material has a relative dielectric constant of about three, the characteristic impedance of the variable dispersion meander line having a 2A/D ratio of 2.0 is approximately 46 ohms when adjusted to provide an S/D ratio of 0.15 and the resultant 180° fundamental to second harmonic phase difference. In a circuit application wherein the characteristic impedance must be maintained within certain acceptable limits, e.g., 50 ohms $\pm$ 10 ohms, this value of 46 ohms is well within the acceptable limits at the S/D ratio of 0.15 and permits adjustment on either side of the 0.15 S/D ratio.

It can be seen from the foregoing description that the variable dispersion meander line of the present invention may provide a continuously variable dispersion characteristic within desired limits while substantially maintaining the characteristic impedance of the line within an acceptable range.

The disclosed variable phase dispersion technique may be readily adapted for use in harmonic cancellation in microwave systems and can be applied to other systems wherein phase equalizers or variable time delay devices are employed.

WHAT WE CLAIM IS:—

1. A variable electrical delay line comprising a first member having a first electrical conductor which provides a plurality of electrically interactive, phase dispersive segments spaced along the length thereof; a second member overlying at least one of said segments of said first member and including a second electrical conductor overlying said segment of the first conductor for varying the electrical interaction between the segments of the first conductor as a result of relative movement between said first and second members.

2. A variable delay line according to claim 1, characterized in that the second electrical conductor includes a plurality of electrically interactive, phase dispersive segments overlying said first member, the segments of the second conductor being at least partially coextensive with and electrically contacting associated ones of the segments of the first conductor to constitute respective combined segments.

3. A variable delay line according to claim 1 or 2 characterized in that each of said combined segments has a width W measured along the length of the first member and said combined segments are spaced by a distance S along the length of the first member, the second electrical conductor varying the ratio of the spacing S to the distance S+W as a result of said relative movement.

4. A variable delay line according to any of the preceding claims, characterized by first and second terminals connected to said first conductor.

5. A variable delay line according to any of the preceding claims characterized in that the first and second conductors are each substantially planar and are carried respectively by said first and second members in sliding contact with each other.

6. A variable delay line according to any of the preceding claims characterized in that said first and second members are substrates.

7. A variable delay line according to any of the preceding claims characterized in that said first and second conductors are strips.

8. A variable delay line according to any of the preceding claims characterized in that said first and second conductors are disposed on the first and second members as meandering conductors.

9. A variable electrical delay line substantially as hereinbefore described with reference to and as illustrated in Figures 2A—7.

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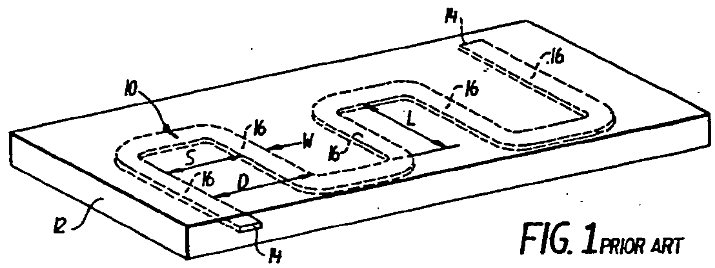


FIG. 1 PRIOR ART

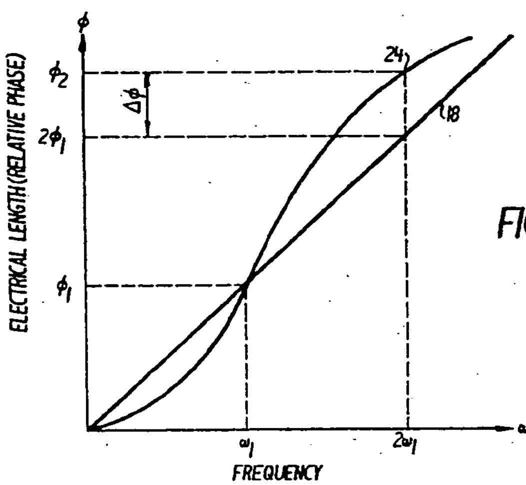
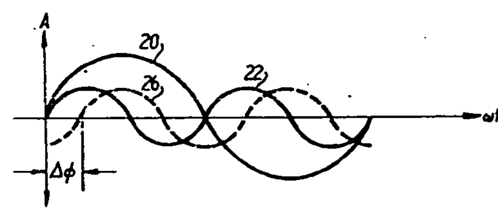


FIG. 2A

FIG. 2B



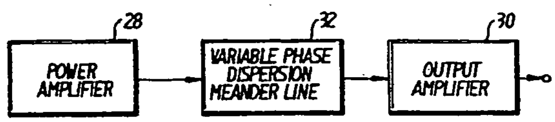


FIG. 3

FIG. 4

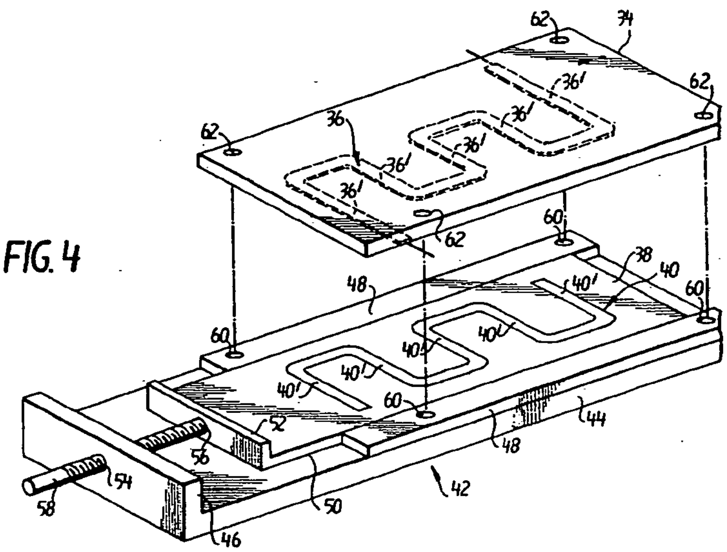


FIG. 5A

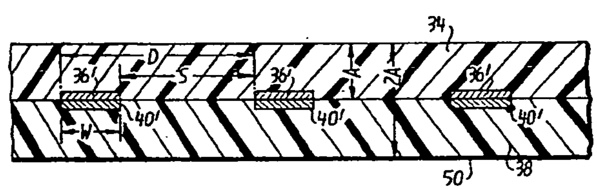
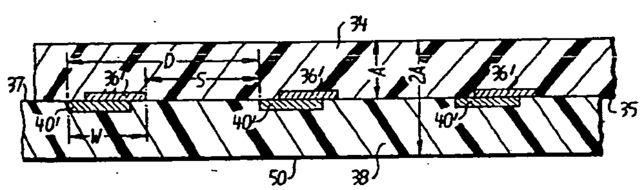


FIG. 5B



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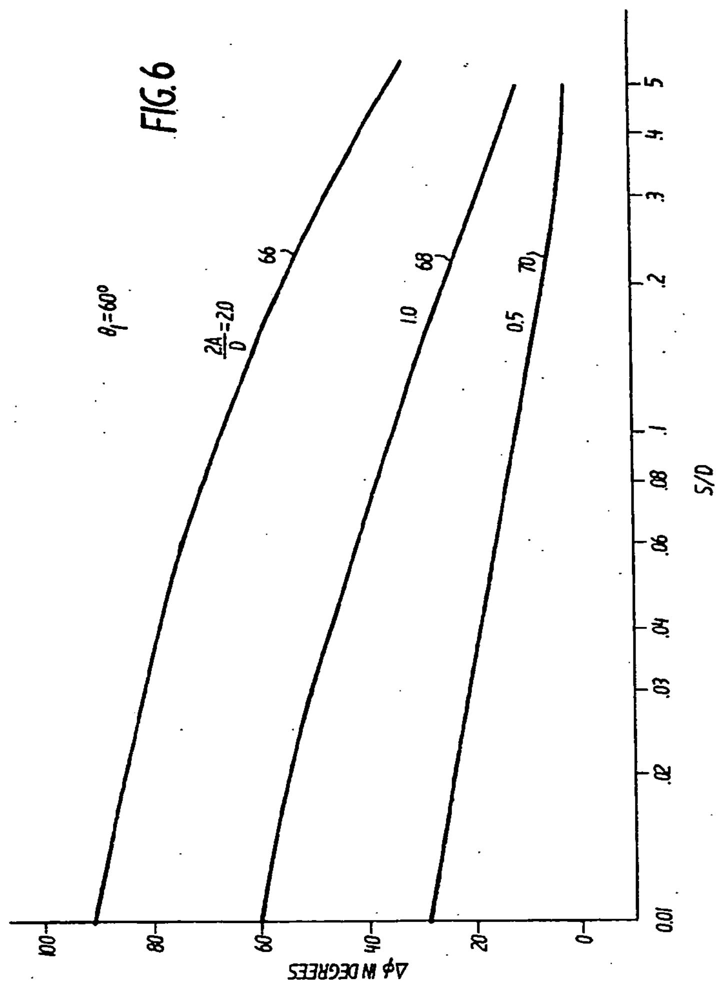

FIG. 6

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FIG. 7